AD-A094 829 RAND CORP SANTA MONICA CA F/G 5/10

DIFFERENCES IN SPATIAL KNOWLEDGE ACQUIRED FROM MAPS AND NAVIGAT--ETC(U)

DEC 80 P W THORNDYKE, B HAYES-ROTH N00014-78-C-0042

UNCLASSIFIED RAND/N-1595-ONR NL

1 OF 1

AD A
094829

END

DATE FILMED

8-81

DTIC

(12)

LEVEL II

A RAND NOTE

DIFFERENCES IN SPATIAL KNOWLEDGE ACQUIRED FROM MAPS AND NAVIGATION

Perry W. Thorndyke and Barbara Hayes-Roth

November 1980

N-1595-ONR

Prepared For

The Office of Naval Research

Rand
SANTA MONICA, CA. 90406

This research was sponsored by the Personnel and Training Research Programs, Psychological Sciences Division, Office of Naval Research, under Contract No. N00014-78-C-0042, Contract Authority Identification Number NR 157-410.

Published by The Rand Corporation

A RAND NOTE

DIFFERENCES IN SPATIAL KNOWLEDGE ACQUIRED FROM MAPS AND NAVIGATION

Perry W. Thorndyke and Barbara Hayes-Roth

November 1980

N-1595-ONR

Prepared For The Office of Naval Research

Rand
SANTA MONICA, CA. 90406

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: N-1595-ONR	2. GOVT ACCESSION NO.: AD-A094 829
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): Differences in Spatial Knowledge Acquired from Maps and Navigation	5. TYPE OF REPORT & PERIOD COVERED: Interim
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): P. W. Thorndyke, B. Hayes-Roth	8. CONTRACT OR GRANT NUMBER(s): N00014-78-C-0042-ONR
9. PERFORMING ORGANIZATION NAME AND ADDRESS: The Rand Corporation, 1700 Main Street, Santa Monica, CA 90406	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: NR 157-410
11. CONTROLLING OFFICE NAME AND ADDRESS: Personnel and Training Research Programs, Office of Naval Research (Code 458), Arlington, VA 22217	12. REPORT DATE: December 1980
	13. NUMBER OF PAGES: 57
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release: Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

No Restrictions

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Maps
Learning
Psychology
Perception (Psychology)
Reasoning

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

See Reverse Side

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Proposes models of the spatial knowledge people acquire from maps and navigation and the procedures required for spatial judgments using this knowledge. From a map people acquire survey knowledge encoding global spatial relations. This knowledge resides in memory in images that can be scanned and measured like a physical map. From navigation people acquire procedural knowledge of the routes connecting diverse locations. People combine mental simulation of travel through the environment and informal algebra to compute spatial judgments. An experiment in which subjects learned an environment from navigation or from a map evaluates predictions of these models. With moderate exposure, map learning is superior for judgments of relative location and straight-line distance among objects. Learning from navigation is superior for orienting oneself with respect to unseen objects and estimating route distances. With extensive exposure, the performance superiority of maps over navigation vanishes. These and other results are consonant with the proposed mechanisms.

PREFACE

This Note describes completed research undertaken at Rand for the Office of the Director of Personnel and Training Research Programs, Psychological Sciences Division, Office of Naval Research, under Contract No. N00014-78-C-0042. The reported research represents a portion of a larger research effort investigating the knowledge and procedures that people use to learn and reason with spatial knowledge of their environment. The Note should interest both researchers studying human spatial cognition and practitioners concerned with the training of orientation and navigational skills.

SUMMARY

This Note proposes models of the spatial knowledge people acquire from maps and navigation and the procedures required for spatial judgments using this knowledge. From a map, people acquire survey knowledge encoding global spatial relations. This knowledge resides in memory in images that can be scanned and measured like a physical map. From navigation people acquire procedural knowledge of the routes connecting diverse locations. People combine mental simulation of travel through the environment and informal algebra to compute spatial judgments. An experiment in which subjects learned an environment either from navigation or from a map evaluates predictions of these models. When subjects have moderate exposure, map learning is superior for judgments of relative location and straight-line distances among objects. Learning from navigation is superior for orienting oneself with respect to unseen objects and for estimating route distances. With extensive exposure, the performance superiority of map learning vanishes. These and other results are consonant with the proposed mechanisms.

CONTENTS

I. INTRODUCTION

Point to the Statue of Liberty from where you are sitting. Now point to the local airport from where you are sitting. These tasks illustrate the use of different types of spatial knowledge to compute an orientation judgment. For the first task, most individuals use a mental image of a map of the United States and an estimate of their current compass bearing to compute the direction of the Statue of Liberty. For the second task, most individuals use knowledge of the route from their present location to the airport to estimate its direction. Even grade-school children can use these two types of knowledge and computational processes to perform orientation judgments (Lord, 1941).

These examples illustrate two of the many real-world problems requiring spatial cognition--that is, the acquisition and use of knowledge about large-scale space.[1] While these examples perhaps overgeneralize and oversimplify the methods people use to produce their estimates, they illustrate three important points about spatial cognition. First, people have various types of spatial knowledge that they acquire from different sources (e.g., maps, navigation experience, verbal descriptions or directions, photographs). For example, one might acquire a spatial overview of a town by studying a map, and detailed route knowledge from navigation. Second, people use different procedures

[1] We use the term large-scale space to refer to an area large enough for a person to navigate, the structure of which cannot be observed from a single viewpoint on the ground.

to make spatial judgments, depending on the type of knowledge they have. As illustrated above, a person might judge the direction of a destination differently when using a learned map than when using knowledge derived from navigation. Finally, the accuracy of a spatial judgment depends on the accuracy of both the underlying knowledge and the computational procedure operating on the knowledge. Thus, for example, a person may have an accurate mental map of the United States but may err when computing the direction of the Statue of Liberty.

Much prior research has investigated the accuracy of spatial knowledge acquired through navigation experience (Acredelo, Pick, & Olsen, 1975; Hardwick, McIntyre, & Pick, 1976; Hart & Moore, 1973; Piaget & Inhelder, 1967; Piaget, Inhelder, & Szeminska, 1960; Shemyakin, 1962; Siegel & White, 1975; Siegel, Kirasic, & Kail, 1978; Thorndyke, 1980a). However, direct comparisons of performance based on different types of learning experiences have considered only route-following (Wetherell, 1979) or route-planning (Bartram, 1980) tasks. No studies have investigated people's ability to orient themselves, estimate distances, or locate relative positions of objects under different learning conditions.

This Note investigates differences in spatial knowledge and estimation procedures derived from two typical sources of information about large-scale space: maps and navigation experience. The remainder of the Note is organized as follows. We first review briefly previous research in spatial knowledge acquisition. We then elaborate on the earlier theoretical work by distinguishing between the knowledge that individuals acquire from maps and the knowledge they acquire from

navigation, and by postulating how this knowledge changes with repeated exposure to the knowledge source. Next, we describe an experiment in which subjects exposed to one of these two types of spatial knowledge judged relative object location, oriented themselves in the environment with respect to unseen locations, and estimated euclidean (straight-line) and route distances. We treat the results and discussion of the experiment in two sections--one focusing on the distance-estimation tasks, the other focusing on the object-placement tasks (location and orientation). In each section, we present process models for how subjects produce their judgments from memory of either a map or traversed routes in the environment. The models support a variety of predictions of the relative accuracy of subjects' judgments. We then present the experimental data and evaluate the predictions in light of these data.

II. KNOWLEDGE REPRESENTATIONS FOR LARGE-SCALE SPACE

Much prior research has investigated the knowledge people acquire about the space around them. In environmental psychology, numerous studies have investigated correlations between a variety of subject variables (e.g., socioeconomic status, length of residence, age, and other personal attributes) and the detail and accuracy of subjects' reproduced maps of their locale (e.g., Appleyard, 1970; Canter, 1977; Downs & Stea, 1973, 1977; Evans, 1980; Golledge & Rushton, 1976; Milgram & Jodelet, 1976; Moore & Golledge, 1976). These studies have demonstrated that the type and amount of spatial knowledge people have change with increased familiarity with the environment. Generally, however, such studies do not control subjects' environmental experiences, so it is unclear how and from what sources subjects derive their knowledge.

In contrast, research in developmental psychology has investigated spatial knowledge acquired solely from navigation (Hardwick, McIntyre, & Pick, 1976; Herman & Siegel, 1977; Siegel, Kirasic, & Kail, 1978; Siegel & White, 1975). These studies have demonstrated that subjects' knowledge of the locations of objects in the environment becomes more accurate with increased experience. Most researchers interpret these changes as qualitative shifts in the representation of space from memory for traversed routes to a more abstract, map-like representation of object locations (Appleyard, 1969, 1970; Piaget, Inhelder, & Szeminska, 1960; Siegel, Kirasic, & Kail, 1978; Siegel & White, 1975; Shemyakin, 1962). However, these studies have not investigated the supposed similarities between judgments based on maps and judgments based on

experientially derived knowledge.

Nevertheless, this earlier research has suggested a gross theoretical distinction between procedural descriptions and survey knowledge (Siegel & White, 1975; Thorndyke, 1980b; Thorndyke & Hayes-Roth, 1978, Note 1). Procedural descriptions refer to knowledge acquired about the routes between locations. Such knowledge typically derives from direct navigation experiences and encodes a sequential record of the space between start points, subsequent landmarks, and destinations. At a minimum, a procedural description of the route between A and B must identify locations at which the navigator must change direction and specify the action to be taken at those locations (e.g., "turn right at the corner of Ocean Avenue and Wilshire Boulevard"). This sequence of prescribed actions may be thought of as a set of stimulus-response pairs or condition-action rules (Kuipers, 1978; Thorndyke, 1980b).

Typically, however, a person's procedural knowledge contains more detailed information about the traveled route. The information might include impressions of the distance traveled along each leg (straight-line segment) of the route, the angle of the turns between legs, and terrain features along the route. This representation, then, contains sequentially organized knowledge of details at different locations in the space.

In contrast, survey knowledge refers to knowledge of the topographic properties of an environment. These properties include the location of objects in the environment relative to a fixed coordinate system (e.g., compass bearings), the global shapes of large land features (e.g., streets, parks, lakes), and the inter-object euclidean

(i.e., straight-line) distances. Such information is not available from direct experience in the environment, but is portrayed on maps. Thus, people frequently learn maps and use them to make routine spatial judgments (Kosslyn, Ball, & Reiser, 1978; Thorndyke, 1979). We assume that when learning maps intentionally, people encode the spatial information on them in image-like representations.

In making this assumption, we do not wish to raise fundamental representational issues (Anderson, 1978; Hayes-Roth, 1979). We acknowledge that it may be possible to represent survey knowledge in discrete propositions (e.g., Kuipers, 1978; Stevens & Coupe, 1978). However, our evidence indicates that people use mental images to learn maps and to scan previously learned maps to judge spatial relations (Thorndyke, 1979; Thorndyke & Stasz, 1980). Therefore, throughout the following discussion we assume an isomorphism between the mental representation of a map and the physical map.

Our theory distinguishes what people learn from maps and navigation in terms of five features: the content of the memory representation, the dimensionality of the memory representation, the individual's perspective on the memory representation, procedures operating on the memory representation, and the effects of practice on the first four features. Table 1 summarizes these differences. The assumptions of our theory for each of these features are discussed in detail below.

KNOWLEDGE ACQUISITION FROM MAPS

Content of the memory representation. In studying a map, the individual acquires survey knowledge of the depicted space. This knowledge

Table 1

DIFFERENCES IN KNOWLEDGE ACQUIRED FROM MAPS AND NAVIGATION

Feature	Knowledge Source	
	Map	Navigation
Contents of Memory	Image of studied map	Memory for traversed routes
Dimensionality	Two-dimensional	Four-dimensional
Perspective	Canonical vertical	Canonical horizontal
Procedures	Inspection and measurement	Simulation and computation
Effects of Practice	Acquisition of details Strengthening of representation	Acquisition of details Strengthening of representation Organization of components Development of translucence

encodes topographical properties of the space, including the locations of objects relative to a fixed coordinate system (e.g., compass bearings), the global shapes of large environmental objects (e.g., streets, parks, lakes), and inter-object euclidean distances.

Dimensionality of the memory representation. Like the map, the memory representation is a two-dimensional rendering of the space. These dimensions typically correspond to the horizontal dimensions of the environment.

Perspective on the memory representation. The individual's perspective on the memory representation corresponds to the canonical vertical view he or she has of the studied map. The individual "views" the

memory representation from above and outside of the depicted space. Just as the map is an external object to be examined visually, its memory representation is an object to be examined cognitively.

Procedures applied to the memory representation. The individual judges spatial relations, using the memory representation with essentially the same procedures he or she uses on external maps. Visual search permits the individual to identify the exact and relative locations of particular objects. Measurement procedures permit the individual to assess euclidean distances and compass bearings between objects.

Effects of practice. Increasing study of a map adds previously unlearned details to the representation. All of the representation's elements become strengthened in memory and are more easily retrievable.

KNOWLEDGE ACQUISITION FROM NAVIGATION

Content of the memory representation. During navigation, the individual acquires procedural knowledge of the environment. This knowledge encodes observed features in the environment and action sequences to be performed to navigate among locations. A typical action in a sequence describes a behavior to be executed at a particular location (e.g., turn right at the corner of Sunset Boulevard and Rockingham Avenue).

Dimensionality of the memory representation. Like the experience of navigation, memory representations derived from navigation are four-dimensional renderings of the space. These dimensions correspond to the one vertical and two horizontal dimensions of the environment, plus a temporal dimension.

Perspective on the memory representation. The individual's perspective on the memory representation corresponds to the canonical horizontal view he or she has of the environment during navigation. That is, the individual "views" the representation from some point on the ground. This implies that the individual is cognitively inside of the memory representation. Just as the environment is a physical space within which the individual navigates, its memory representation is a cognitive space within which the individual cognitively navigates.

Procedures applied to the memory representation. The individual brings to bear on the memory representation essentially the same procedures he or she brings to bear during navigation. Mental simulation of navigation in the environment permits the individual to identify the route distances between objects, the sequence of features encountered along the route, and the actions performed when navigating between points. Computational procedures permit the individual to assess euclidean distances and compass bearings between objects, based on the raw data obtained from mental simulation.

Effects of practice. Increasing navigation experience affects both the content of the memory representation and the individual's perspective on it. As with increasing map study, previously unlearned details are added to the representation and all of its elements become strengthened and more easily retrievable. In addition, the content of the memory representation becomes more organized. The individual identifies points of intersection for multiple routes and adopts a canonical reference frame (e.g., canonical directions). The individual could, theoretically, then compute relative object locations and euclidean

distances from route distance knowledge and knowledge of compass bearings along the routes. Individuals rarely make such computations and consciously store their results. However, we assume automatic, unconscious procedures permit integration and organization of memory and the induction of survey knowledge capturing topographical properties of the environment.

Indeed, numerous studies have found that survey knowledge improves with increasing residence in a community (e.g., Appleyard, 1970; Golledge & Zannaras, 1973; Ladd, 1970), although such studies have failed to control subjects' access to maps or other direct sources of survey knowledge. In laboratory studies using controlled exposures to the environment, subjects with limited navigation experience demonstrate accurate procedural knowledge but nonveridical survey knowledge. However, their survey knowledge and orientation ability generally improve with increasing numbers of trips through the environment (Allen, Siegel, & Rosinski, 1978; Herman & Siegel, 1977; Kozlowski & Bryant, 1977).

As survey knowledge develops, the individual's perspective on the environment changes to permit the use of the newly acquired topographical information. We conceptualize this change as the development of translucence in the representation. That is, the individual can essentially "view" distant objects in the environment through intervening objects along a straight line of sight, just as he or she can view any object on a map along a straight line of sight. Similarly, the individual can simulate straight-line traversal between two points without having to circumnavigate intervening objects.

To test our theory, we devised an experiment in which subjects learned locations in an environment either by memorizing a map or by navigating in the environment. They then performed a variety of spatial judgments using their knowledge of the space. We formulated process models for the procedures that subjects with different learning experiences would use to compute their estimates. These models, combined with our assumptions about the memory representations acquired from different experiences, supported a variety of predictions for subjects' performance on the tasks. We first present our experimental method, then a detailed discussion of our process models and attendant predictions.

III. EXPERIMENTAL METHOD

MATERIALS

For our experiment, we sought an environment that would be relatively easy to learn yet sufficiently complex to make the tasks of orientation, location, and distance estimation somewhat difficult. We selected the first floor of The Rand Corporation in Santa Monica. Figure 1 shows this environment to accurate scale, with its correct compass orientation. The space comprises two buildings separated by an enclosed hall with a 120-degree jog. The buildings contain several prominent public areas (the labeled, darkened areas on the map), a maze of hallways (indicated by the white lines running through the buildings), offices (indicated by the shaded areas surrounding the halls), and interior courtyards (indicated by the white rectangles on the floor plan of the larger building). The distance from the Northwest Lobby to the South Lobby is 627 feet along a straight line and 877 feet via the shortest set of hallways. With the exception of the hall connecting the two buildings, all hallways intersect at right angles. However, because of the relative orientation of the two buildings, it is nontrivial to orient oneself with respect to locations in a different building or to produce an accurate map of the environment based on limited navigation experience.

SUBJECTS

Forty-eight female volunteers participated for pay. Subjects in the navigation-learning conditions were secretaries or research assistants employed at Rand. These subjects' highest level of educational

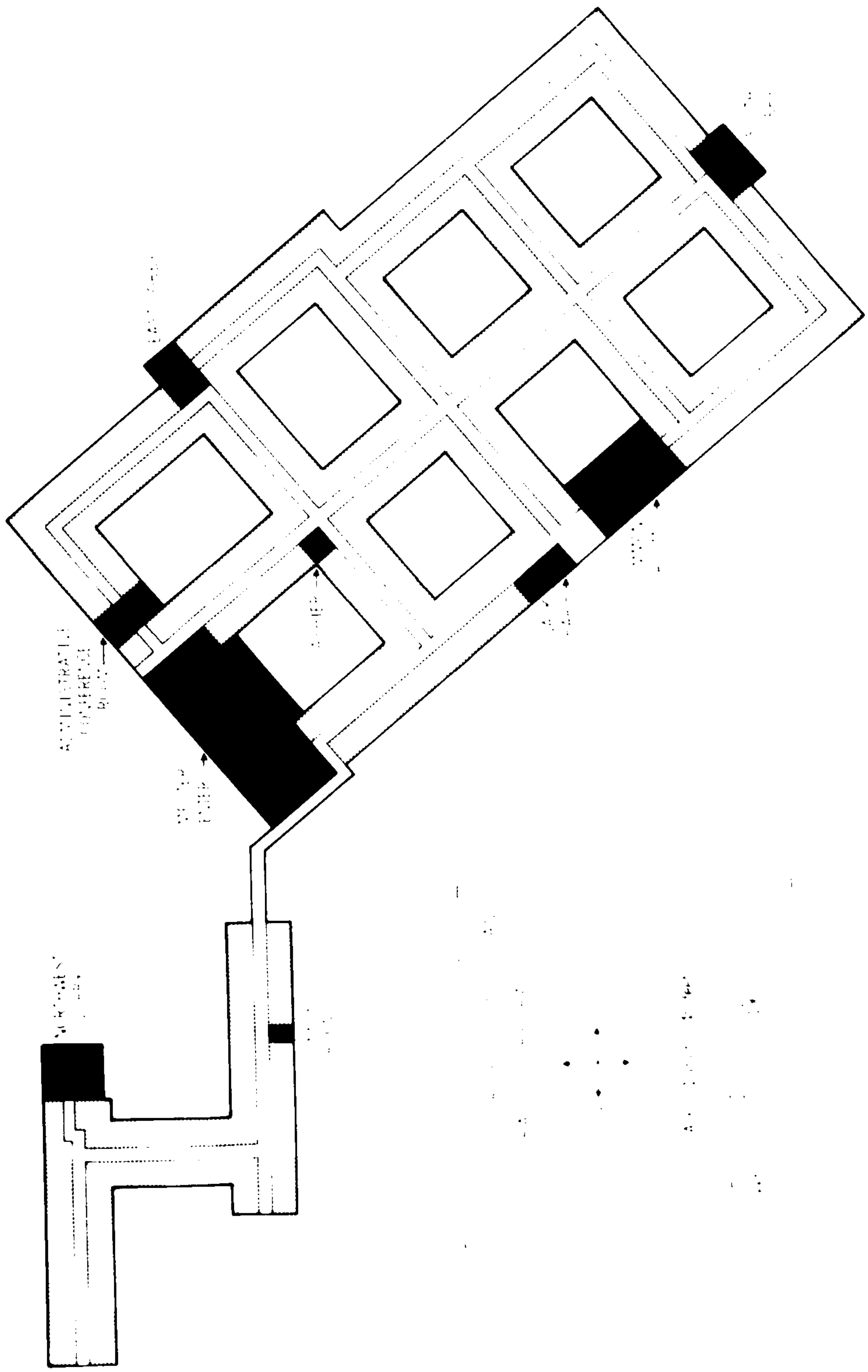

Fig. 1--The map of the environment used in the experiment

achievement was a high-school diploma or a B.A. degree. Subjects in the map-learning conditions were students at Santa Monica College.

DESIGN

The subjects were divided into two training conditions with 24 subjects in each. In the navigation condition, subjects' knowledge of locations within Rand derived solely from navigation experience. None of these subjects reported having studied a map of the floor plan during their employment at Rand. In the map-learning condition, no subject had been inside Rand prior to the experiment. These subjects acquired knowledge of locations and halls within Rand solely from studying the map shown in Figure 1.

Within each training condition, there were three groups of subjects, differing in the amount of exposure they had had to the spatial information. The navigation subjects had worked at Rand for either 1 to 2 months, 6 to 12 months, or 12 to 24 months. Each group contained eight subjects. The map-learning subjects differed in the amount of time they were permitted to study the map. One group studied the map until they could redraw it without error in the configuration or placement of halls and locations. A second group studied the map until they reached this criterion and then spent an additional 30 minutes studying it. The third group studied the map beyond the criterion for an additional 60 minutes.

The set of test items comprised 42 pairs of locations within Rand. The first location of each pair was designated the start point; the second location, the destination. The 42 pairs were composed by cross-

ing six start points (Supply Room, Computer Center, Administrative Conference Room, East Lobby, Snack Bar, and South Lobby) with seven destinations (the Northwest Lobby, the Cashier, and the remaining five start points).

For each test item, subjects performed five judgments: route distance (the distance from the start point to the destination along the hallways), euclidean distance (the straight-line distance from the start point to the destination), orientation (pointing to the destination from the start point), simulated orientation (while in a closed office, pointing to the destination from an imagined position at the start point), and location (indicating the location of the destination on a piece of paper containing the start point and another reference point).

PROCEDURE

Subjects were tested individually. The experimenter informed each subject that the purpose of the study was to assess the accuracy of people's spatial knowledge, given different types and amounts of learning experience.

Each map-learning subject was seated in the experimenter's office and told she was to learn the floor plan of Rand (shown in Figure 1), including the shape of the buildings, the names and locations of the public areas, and the directions of the halls through the buildings. Although the map contained scale information, the experimenter did not instruct the subjects to learn metric distances. Each subject studied the map on a series of study-recall trials. On each trial, the subject was given a copy of the map to study for 2 minutes. At the end of this

time, the experimenter removed the map and asked the subject to draw the map on a blank piece of paper. After the subject had completed the drawing, the experimenter provided feedback to the subject on the correct and incorrect features of the map. The subject then studied the map for another 2 minutes. The study-recall cycle was repeated until the subject had depicted the topological properties of the map and labeled it correctly on two consecutive trials. Subjects in the two overlearning groups then continued this study-recall procedure for either 30 or 60 minutes.

Navigation subjects, who had pre-experimental knowledge of Rand from either 1 to 2, 6 to 12, or 12 to 24 months of walking in the halls, received no additional training.

The experimenter then took each subject to the first start point, the Supply Room. The experimenter placed a cardboard compass wheel with a 12-inch radius on the floor in front of the subject. The compass wheel contained rays numbered from 0 degrees to 355 degrees in 5-degree increments. The wheel was oriented such that the 0-degree ray faced north, although this alignment convention was not told to the subject. The experimenter then asked the subject to face in the direction marked 0 degrees. She then informed the subject that she would read to her a succession of locations within Rand. For each location, the subject performed three estimates. First, she indicated to the nearest degree the direction to the center of the destination room. Second, she estimated the distance in feet to the center of the destination room along the ray indicated by the previous judgment (i.e., the euclidean distance). Third, she estimated the distance in feet to the destination

along the shortest path through the hallways. The experimenter explicitly indicated the precise route she wished the subject to estimate, in order to avoid any ambiguity about the shortest route. To aid the subjects in estimating distances, the experimenter told each of them that the distances from the center of the Snack Bar to the center of the Common Room and across the Computer Center were both 100 feet.

When the subject had performed the seven sets of estimates from the Supply Room, the experimenter led her to the next start point, the Computer Center. The procedure was repeated in identical fashion, except that the compass wheel was aligned in this room (and all subsequent start points) so that the 0-degree ray was parallel to the minor axis of the building (i.e., at a compass bearing of 120 degrees). Thus, at all start points the 0-degree ray was parallel or perpendicular to the walls of the room. All subjects visited the start points and estimated destination points in the same order.

After visiting the six start points, the subject and experimenter returned to the experimenter's office. The experimenter seated the subject at a table with the compass wheel in front of her and told her to imagine herself at the first start point. Then, the subject again estimated the bearing of each of the destination points on the compass wheel. This "simulated orientation" task was repeated for each of the 42 pairs in the same order as on the earlier orientation task. We included this task to control for any potential advantage the navigation subjects might have gained during the orientation task by using local visual cues to refine their orientation estimates. These cues, if used, might not have benefited map-learning subjects because of their

unfamiliarity with the Rand buildings.

After completion of the simulated-orientation task, the experimenter gave the subject a booklet containing 42 8.5 x 11-inch pages. On each page, labeled dots designated the locations of two of the public areas within Rand (e.g., East Lobby, Common Room). One of the labels was circled, indicating that that location should be considered the start point. The upper left-hand corner of the page contained the name of a destination (e.g., Cashier). These 42 items contained the same start point-destination pairs as the previous tests.

The subject's task was to place a dot on the page indicating the location of the destination relative to the start point, using the second given point to establish the scale and orientation of this simplified map. For these test items, the two given points appeared in arbitrary locations on the page with the constraints that (1) the scale of the map was the same as that of the original map studied by the map-learning subjects, and (2) the correct location of the destination point was within the boundaries of the page. The subject's work on this task was self-paced, and unlimited time was provided for completion.

IV. DISTANCE ESTIMATION

PREDICTIONS

We assume the procedures subjects use to estimate distances depend on their representation of spatial knowledge. Thus, subjects who have learned a map estimate distances differently from subjects who have direct navigation experience. In each case, we presume that subjects retrieve from memory their knowledge of the space to be estimated and compute from this knowledge the required response. Table 2 summarizes our models of the procedures subjects with the two types of learning experience use to estimate euclidean and route distances.

Table 2

PROCEDURES FOR DISTANCE ESTIMATION

Type of Experience	Type of Estimate: Euclidean	Type of Estimate: Route
Map	Visualize map Locate end points Measure length Generate response	Visualize map Locate end points Measure leg lengths Sum lengths Generate response
Navigation	Mentally simulate route Estimate leg lengths Estimate turning angles Perform informal algebra Generate response	Mentally simulate route Estimate leg lengths Sum lengths Generate response

Subjects who have learned a map generate and use an image of the map to estimate distances. They measure distances by scanning from the specified start point to the destination point in a manner analogous to the way in which they would scan across an actual map (Thorndyke, 1979). When estimating a euclidean distance, subjects perform a single scan and estimate the distance by comparing it to the provided scale distance. When estimating a route distance, subjects must estimate and sum the lengths of the component legs on the route to arrive at an overall estimate. The additional processing required to aggregate the component estimates can introduce error into the estimation process. In general, the more component legs to be estimated and combined, the greater the opportunity for error.

Subjects with navigation experience estimate the distance between two points by mentally simulating a trip from the start point to the destination. When estimating route distances, they estimate and sum the lengths of the component legs on the route. When estimating euclidean distances, they must also estimate the angles at which they turn between different legs on the route. They must then perform some mental algebra using the leg and angle estimates to estimate the straight-line distance between the points. For example, if subjects encountered a right-angle turn on a two-leg route, they could estimate the euclidean distance between the start and destination point, using the Pythagorean theorem. While we do not believe that subjects actually perform this computation, we do think they use informal, analog equivalents of it to produce a judgment. Since euclidean distance estimation requires more data and

computation than route distance estimation, euclidean estimates should be less accurate than route estimates.

Using these models and the previous assumptions regarding the effects of learning experience and practice, we made 13 specific predictions for the distance estimation performance of subjects with either navigation or map-learning experience. We present these predictions below, followed by data from the experiment that evaluate the predictions.

Our first set of performance measures assessed the overall accuracy of subjects' internal representations of the location of objects (i.e., their cognitive maps) based on their distance estimates. We sought a measure of the accuracy of subjects' reconstruction of relative distances rather than simply an item-by-item measure of absolute accuracy. Consequently, we elected to compute the Pearson correlation between subjects' estimated distances and the true distance for each type of estimate. This provided a measure of consistency in the accuracy of multiple judgments that was insensitive to absolute errors, thus allowing for a scale factor in each subject's estimates. The first seven predictions are based on this dependent variable.

Prediction 1. The cognitive maps of navigation subjects should be more accurate when derived from route estimates than from euclidean estimates. When navigation subjects estimate route distances, they simulate traversal of the route as a basis for the distance judgment. The difficulty of computing this estimate changes little as the length and complexity of the route increases. However, euclidean estimates require computations that become more complex and more subject to error

as the complexity of the route increases. Therefore, we expected that the correlation between navigation subjects' true and estimated distances would be higher for route than for euclidean estimates.

Prediction 2. The cognitive maps of map-learning subjects should be equally accurate when derived from route or euclidean estimates. For both estimates, subjects measure distances directly on their learned maps. Since route estimation requires multiple measurements, it is slightly more complex than euclidean estimation. However, this procedural difference is small compared to the different estimation processes of navigation subjects. We therefore expected no significant difference between the configurational accuracy of map-learning subjects' two types of estimates.

Prediction 3. Euclidean distance estimates of navigation subjects should improve with experience. As these subjects acquire more experience, they induce survey knowledge of the environment. This knowledge can support direct measurement of the euclidean distance between two points without reference to the route connecting them. Thus, the correlation between true and estimated euclidean distances should increase across experience groups.

Prediction 4. Route distance estimates of navigation subjects should not improve with experience. Since our least experienced navigation subjects were familiar with all tested routes, they were presumably able to use a navigation simulation to produce their estimates. The procedure used to produce these estimates does not change with practice. Therefore, the overall accuracy of these estimates should not improve.

Prediction 5. Neither euclidean nor route distance estimates of map-learning subjects should improve with practice. Since all map-learning subjects had learned the map perfectly, they possessed the knowledge needed to estimate both types of distances. We had no reason to expect the accuracy of these estimates to improve with overlearning.

Prediction 6. Map-learning subjects should estimate euclidean distances more accurately than navigation subjects with minimal experience. Map-learning subjects measure euclidean distances directly, while navigation subjects with little experience compute these estimates from their route knowledge, using a complex and imprecise procedure. Therefore, map-learning subjects' estimates should be more accurate.

Prediction 7. Navigation subjects with extensive experience should estimate euclidean distances as accurately as map-learning subjects. Navigation subjects with extensive experience estimate euclidean distances directly, using survey knowledge. As this knowledge becomes more precise and accurate, the accuracy of the euclidean estimates derived from it should approximate that of subjects who have learned a map.

The remainder of the predictions address the absolute errors in subjects' judgments. Based on the postulated computational procedures given in Table 1, we generated six qualitative predictions for the relative accuracy of particular estimates. Each of these predictions is based on the assumption that increasing the number of computations required to produce an estimate increases the absolute error in the estimate. Thus, for example, we would predict that the error in a route estimate requiring the summation of three component-leg estimates should exceed the error in an estimate requiring a single measurement in

memory. In fact, component errors could cancel each other and result in a more accurate overall estimate than that resulting from the single computation. Thus, our assumption underestimates the error in subjects' judgments. However, in all cases any underestimate works against our observing the error differences we predict. We thus are testing our hypotheses in their strongest form.

Prediction 8. The error in map-learning subjects' estimates of route distances should exceed the error in their estimates of euclidean distance. For a given start point and destination point, the euclidean estimate requires the measurement of a single distance. On the other hand, the route estimate requires the summation of several component estimates. Therefore, on average, the route distance error should exceed the euclidean distance error.

Prediction 9. The error in navigation subjects' estimates of euclidean distance should exceed the error in their estimates of route distance. The additional computation required to produce euclidean estimates using route estimates presents opportunities for error in angle estimation or in informal algebra. Thus, euclidean estimates should be less accurate.

Prediction 10. The accuracy of navigation subjects' estimates of euclidean distances should be limited by the accuracy of their component-leg estimates. For a given start point and destination point, a subject's euclidean estimate is computed from estimated leg lengths and turning angles. Thus, the error in the euclidean estimate should be at least as large as that computed from the subject's component-leg estimates, the correct turning angles, and error-free algebraic

computations using these data.

Prediction 11. The error in navigation subjects' estimates of euclidean distance should increase as the number of legs on the connecting route increases. Since euclidean estimates utilize route-leg estimates and additional computation, increasing the complexity of the computation and number of component estimates should increase the error of the overall estimate.

Prediction 12. The error in map-learning subjects' estimates of euclidean distance should be independent of the number of legs on the connecting route. These subjects' euclidean estimates do not depend on the connecting route. Hence route complexity should not influence the accuracy of the euclidean estimate.

Prediction 13. The accuracy of all subjects' estimates of route distance should be limited by the accuracy of their component-leg estimates. Since route estimates require the summation of component estimates, the error in the resulting estimate should be at least as large as that predicted by the accurate summation of subjects' component estimates.

EVALUATION OF PREDICTIONS

We tested the first seven predictions using the data provided in Figure 2. Figure 2 contrasts the correlation between the true and estimated distances for both types of estimate. (Across subjects, the absolute error in estimates increased with true distance. Since route distances were longer than euclidean distances, this presented the possibility that route distance correlations may have been artifactually

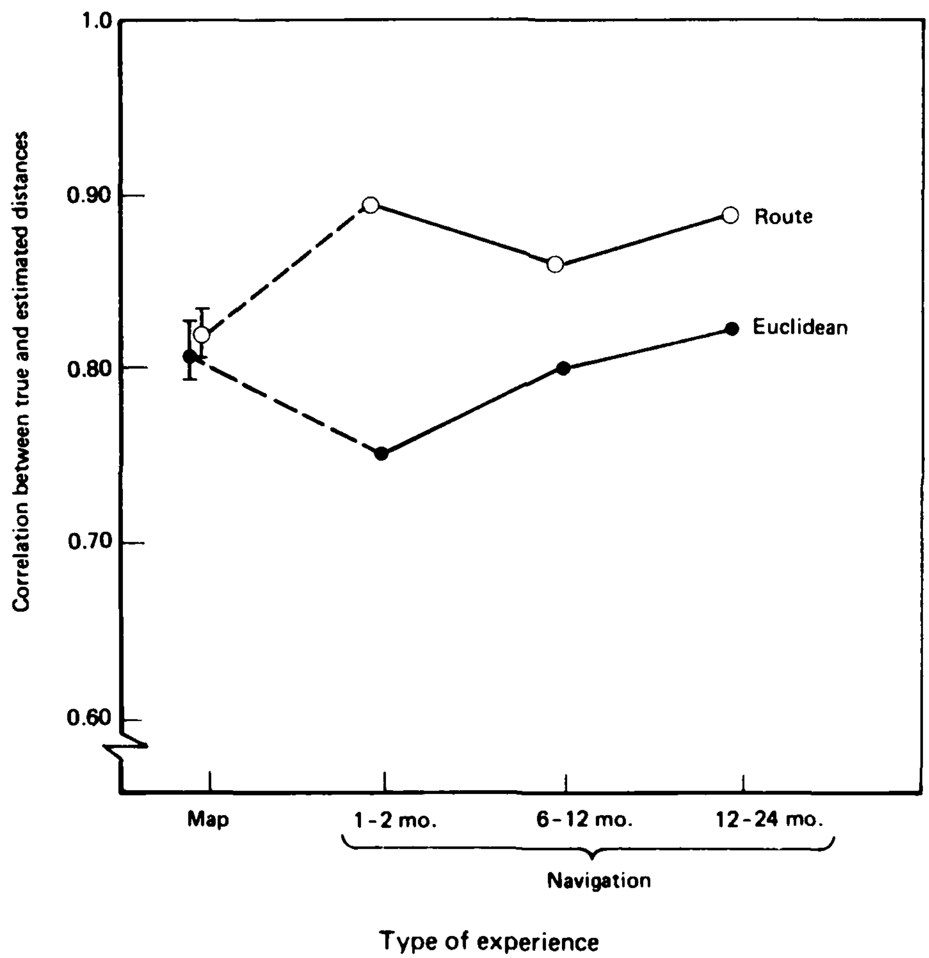

Fig. 2--Correlations between true and estimated distances

depressed relative to euclidean distance correlations. However, correlations computed on rescaled distances that eliminated this artifact did not alter the pattern or reliability of results presented in Figure 2.)

For map-learning subjects, neither the route nor the euclidean correlations varied across experience groups. Therefore, in Figure 2 the data for the three map-learning groups are combined and displayed as a mean value. The bars for each point indicate the range of the mean correlations for the three map-learning subject groups. The failure of map-learning subjects' overall accuracy to improve with overlearning confirms Prediction 5.

As expected from Prediction 2, map-learning subjects' correlations were virtually identical for euclidean and route distance estimates (.82). For exactly half of the 24 subjects, the correlation between true and estimated distances was higher for route than for euclidean judgments. For the other half, the reverse ordering held. For 14 of the 24, the difference between correlations was .05 or smaller. For only two of the 24 subjects was the difference between correlations as large as .10.

In contrast, performance of the navigation subjects was not uniform across experience conditions or judgment types. To contrast the performance of navigation subjects with map-learning subjects, we analyzed the data as a two (types of estimate) by three (levels of experience) factorial experiment with all 24 map-learning subjects treated as a single control group (Winer, 1962).

As expected from Prediction 1, navigation subjects' overall accuracy on route estimates exceeds their accuracy on euclidean estimates. For 23 of the 24 subjects, accuracy on route estimates exceeded accuracy on euclidean estimates. The superiority of route estimates over euclidean estimates was reliable in the analysis of variance, $\underline{F}(2,65) = 31.85$, $\underline{p} < .01$. Predictions 3 and 4 stated that euclidean but not route estimates should improve with experience. Figure 2 shows that in fact euclidean estimates improved, while route estimates remained relatively constant. This interaction was only marginally reliable, $\underline{F}(2,65) = 2.63$, $\underline{p} < .10$. However, post hoc comparisons among individual means indicated that the mean for subjects with 6 to 12 months' experience exceeded that for subjects with 1 to 2 months' experience, $\underline{t}(42) = 1.68$, $\underline{p} < .05$. These data provide weak support for Prediction 3.

We used Dunnett's t-test to contrast the map-learning (control) subjects with each of the six means for navigation subjects (Winer, 1962). For euclidean estimates, map-learning subjects were more accurate than the least experienced navigation subjects ($\underline{p} < .05$) but no more accurate than more experienced subjects. These data confirm Predictions 6 and 7. In addition, all navigation subjects were more accurate than map-learning subjects on route estimates ($\underline{p} < .05$ for each comparison).

To test Predictions 8 and 9, we next contrasted the absolute errors in subjects' individual route and euclidean estimates, as shown in Table 3. While the absolute error in estimates was correlated with true distance for most subjects, the percentage error was not. Therefore, Table 3 presents estimation errors as percentages of true distances.

Table 3

PERCENTAGE ERROR FOR EUCLIDEAN AND ROUTE DISTANCE ESTIMATES

Type of Experience	Type of Estimate: Euclidean	Type of Estimate: Route	Percentage of Subjects Confirming Prediction
Map	40.3	42.0	70.8[a]
Navigation	46.7	36.0	83.3[b]

[a] $p < .05$

[b] $p < .01$

We made Predictions 8 and 9 based on the assumption that increasing the number of mental measurements and the complexity of computation required to produce an estimate increases the error of the estimate. However, we considered one other artifact that could introduce error into the estimation process of map-learning subjects: When people estimate distances by scanning a mental image, obstacles or intervening objects on the route increase the magnitude of the resulting estimate (Thorndyke, 1979). When estimating route distances, subjects following hallways would not encounter intervening objects. However, when estimating euclidean distances, the scanned space might intersect hallways, interior courtyards, offices, or intervening public areas. To minimize the differential effects of clutter on the two types of estimates, we considered in the data presented in Table 3 only those items for which the straight-line route did not pass across an interior courtyard or a public area. Thus, for example, the route between the Supply

Room and the East Lobby was deleted, while the route between the Supply Room and the Snack Bar was retained.

As shown in Table 3, map-learning subjects had larger errors for route estimates than for euclidean estimates. This relationship held for 17 of the 24 subjects ($p < .05$). In contrast, 20 of the 24 navigation subjects made larger errors when estimating euclidean distances than when estimating route distances ($p < .01$). These data strongly support Predictions 8 and 9.

Prediction 10 asserted that the accuracy of navigation subjects' euclidean estimates should be limited by the accuracy of their route-leg estimates. To test this prediction, we computed for each test item the difference between the absolute value of the percentage error in the subjects' euclidean estimate and the absolute value of the percentage error in the estimate computed using the subjects' route-leg estimates, correct values for the angles connecting the legs, and accurate algebraic computation using these data. We then divided this difference by the true distance to obtain a percentage that could be combined across items. Thus, the prediction would be confirmed for a subject whenever this percentage difference, averaged across items, was greater than or equal to zero. Table 4 presents these data. For navigation subjects, the mean across subjects was small but greater than zero. On a subject-by-subject basis, this error difference was zero or positive for 18 of the 24 subjects ($p < .05$). For comparison, Table 4 presents these same data for map-learning subjects, for whom the prediction does not apply. The mean error difference was well below zero for these subjects but was approximately evenly distributed above and below zero. Thus, as

Table 4

PERCENTAGE DIFFERENCE BETWEEN ERROR IN EUCLIDEAN DISTANCE ESTIMATES AND ERROR COMPUTED FROM ROUTE-LEG ESTIMATES

Type of Experience	Percentage Error Difference	Percentage of Subjects Confirming Prediction
Map	-11.4	58.3
Navigation	0.6	75.0[a]

[a] $p < .05$

expected, the positive error difference was obtained only for the navigation subjects.

Table 5 presents the percentage errors in euclidean estimates for items with either few or many legs on the connecting route. As expected

Table 5

PERCENTAGE ERROR IN EUCLIDEAN DISTANCE ESTIMATES FOR LOCATION PAIRS WITH SIMPLE AND COMPLEX CONNECTING ROUTES

Type of Experience	Percentage Error		Percentage of Subjects Confirming Prediction
	1-2 Legs	4-8 Legs	
Map	35.3	38.0	62.5
Navigation	40.7	49.1	66.7[a]

[a] $p < .05$

from Prediction 12, map-learning subjects' estimation error did not increase reliably with the complexity of the connecting route. A nonsignificant 15 of the 24 subjects made larger errors when estimating distances with complex connecting routes. For navigation subjects, the difference between the errors on these two types of items was larger and held for a significant 16 of the 24 subjects, as expected from Prediction 11.

Finally, we tested the prediction that all subjects' route estimates would have larger errors than the errors in their summed component-leg estimates (Prediction 13). To do this, we computed for each item the difference in the absolute value of the percentage error of a subject's route estimate and the absolute value of the percentage error of the estimate obtained by adding the subject's component estimates. For example, for a route from A to C passing through B, we computed

$$\text{Percentage Error Difference} = \frac{|\text{True AC} - \text{Est. AC}| - |\text{True AC} - (\text{Est. AB} + \text{Est. AC})|}{|\text{True AC}|}.$$

For each subject, a difference greater than or equal to zero would confirm the prediction. Table 6 presents the data evaluating this prediction. For both map-learning and navigation subjects, the mean difference was larger than zero. Across all 48 subjects, 30 confirmed the prediction ($p < .05$). As Table 6 shows, the prediction was confirmed more consistently by navigation subjects than by map-learning subjects.

Table 6

PERCENTAGE DIFFERENCE BETWEEN ERROR IN ROUTE DISTANCE ESTIMATES AND ERROR COMPUTED FROM SUMMED LEG ESTIMATES

Type of Experience	Percentage Error Difference	Percentage of Subjects Confirming Prediction
Map	0.5	54.2
Navigation	4.8	70.8[a]
Total	2.7	62.5[a]

[a] $p < .05$

To summarize, our results indicate that map-learning subjects make more errors when estimating route distances than when estimating euclidean distances. However, the accuracy of the relationships among locations as inferred from correlations is equivalent when estimated either from euclidean or route distances. Further, map learners' cognitive maps do not improve with extensive exposure to the map displaying the spatial relationships. Navigation subjects estimate distances and construct cognitive maps from these distances more accurately when considering routes than when considering euclidean relations. With additional navigation experience, the differences between route and euclidean knowledge diminish. Further, subjects with 6 to 12 months' experience performed as well on euclidean estimates and better on route estimates than map-learning subjects. Of our 13 predictions, 12 were reliably confirmed and one was marginally confirmed.

V. ORIENTATION AND OBJECT LOCATION JUDGMENTS

PREDICTIONS

As in the case of estimating distances, we assume that the processes that operate on procedural knowledge to produce orientation and location estimates differ from the processes that operate on survey knowledge. Thus, subjects who have learned a map judge orientation and object location differently from subjects with navigation experience. Table 7 summarizes our models of these procedures. Subjects who have learned a map generate and use an image of the map to judge orientation and location. To perform location judgments, they align their image of the map and the stimulus containing the two given points, by rotating either their image or the paper containing the stimulus. They then rescale their image to the scale of the stimulus and scan across it to determine the location of the destination point. They then transfer this location to the sheet containing the stimuli. Note that the determination of the location of the destination point is independent of the complexity of the route connecting the start point to it.

To perform orientation judgments, map-learning subjects use a similar procedure that requires one additional step. After determining the position from the start point to the destination on their image, they must translate this location from a position vertical to themselves into a response horizontal to themselves. That is, they must translate the perspective from which the response is generated. We assume that this process of perspective translation is difficult and subject to error.

Table 7

PROCEDURES FOR ORIENTATION AND OBJECT LOCATION JUDGMENTS

Orientation Judgment	Location Judgment	
Map-Learning Experience		
Visualize map Locate self Align map with current bearing Find destination Determine angle Translate angle into response plane Generate response	Visualize map Align map with stimulus Rescale map Find destination Determine angle Generate response	
Navigation Experience		
Mentally simulate route Estimate leg lengths Estimate turning angles Perform informal algebra Generate response	Visualize self at start point Mentally simulate route to second given point (Either A or B below)	
	A: Route-fitting method	B: Orientation method
	Translate route into response plane Rescale and align route Simulate route to destination Translate route into response plane Generate response	Perform simulated orientation Translate into response plane Align stimulus with current simulated bearing Simulate route to destination Perform simulated orientation Translate into response plane Generate response

Subjects with navigation experience perform orientation and location judgments by mentally simulating a trip between the start and destination points. When performing orientation judgments, they use a procedure similar to that for determining euclidean distances. These subjects estimate the leg lengths and horizontal turning angles along the route, and then combine these informally to produce a horizontal response in the same perspective as their memory representation. Since the difficulty of computing a response is a function of the number of legs along the simulated route, the accuracy of the judgments should depend on route complexity.

We assume that when estimating the location of a destination point on a sheet containing a start point and a second given point, navigation subjects begin by mentally simulating the route from the start point to the second given point. They then proceed, using either a route-fitting method or an orientation method, as summarized in Table 7.

Using the route-fitting method, subjects change to a vertical perspective on the simulated route in order to represent it on the sheet containing the stimuli. This requires subjects to rescale the estimated leg lengths and to cognitively, if not physically, align the stimulus sheet with their direction of simulated travel on the route. Subjects then simulate traversal of the route between the start point and destination point and translate their perspective on this route into the response plane given by the stimulus sheet. In making this translation, subjects rescale and align the route as indicated by the first translation process. As with map-learning subjects, we assume that changing

perspective on the memory representation in order to produce the appropriate response is difficult and subject to error.

Using the orientation method, subjects first perform a simulated orientation judgment from the start point to the second given point. They then change perspective to translate this response to the plane of the response sheet and align the stimulus, either cognitively or physically, with their current bearing. Having established scale and alignment, subjects then perform a simulated orientation judgment from the start point to the destination point and translate this response to the response plane as before.

Using these models and the previous assumptions regarding the effects of learning experience and practice, we made nine predictions for the orientation and location task performances of navigation and map-learning subjects. As we did with distance estimation, we first present these predictions and then present experimental data that evaluate them.

<u>Prediction 14</u>. <u>Navigation subjects should judge orientation more accurately than map-learning subjects for pairs of points with straight connecting routes</u>. To point toward a destination lying along a straight line of travel, navigation subjects must simply point in the direction of travel. Map-learning subjects performing this task must align their mental maps with their current orientation, determine the angle on the map, and then translate that angle into a pointing response. This more complex procedure should result in larger errors. As the route complexity between the start and destination point increases, the algebraic computation that navigation subjects must perform increases. We have no

estimate of the relative complexity of such computation versus the alignment and response rotation operations of map-learning subjects. Thus, we cannot predict the relative accuracies of judgments between points lying on complex routes.

Prediction 15. Map-learning subjects should judge object location more accurately than navigation subjects. Map-learning subjects judge location by aligning and rescaling their mental maps to correspond to the scale and orientation of the test item. Regardless of the estimation procedure they use, navigation subjects must perform two response rotations to produce an estimate and generate a response. In addition, navigation subjects with minimal experience must compute route lengths and/or orientations to judge locations. Thus, the navigation subjects' task is more complex than the map learners' task and should produce larger errors.

Prediction 16. Orientation and location judgments of navigation subjects should improve with experience. With extensive experience, navigation subjects develop survey knowledge of a space. Such knowledge can support the direct retrieval of object orientations without intermediate computation from route information. This can support both orientation and object location judgments. The simplification of this estimation procedure should increase the accuracy of both types of estimates.

Prediction 17. Orientation and location judgments of map-learning subjects should not improve with experience. Since map learners' knowledge of a space does not change with overlearning, we expect no change in the accuracy with which they retrieve information from their

mental maps. Thus, we predict no change in the accuracy of their orientation or location judgments.

Prediction 18. Navigation subjects should judge orientation more accurately than object location. Regardless of the type of spatial knowledge navigation subjects use to produce their estimates, the location estimation procedure requires the additional operation of changing perspective on the memory representation to generate the required response. Since this introduces error into the estimate, the orientation estimates should be more accurate.

Prediction 19. Map-learning subjects should judge location more accurately than orientation. Map-learning subjects must perform an additional operation to change perspective on the memory representation to generate the pointing response required for the orientation task. Therefore, the orientation estimate should be less accurate than the location estimate.

Prediction 20. The error in navigation subjects' orientation judgments should increase as the number of legs on the connecting route increases. Since orientation judgments utilize route-leg estimates and additional computation, increasing the complexity of the computation and number of component estimates should increase the error of the overall estimate.

Prediction 21. The error in map-learning subjects' orientation judgments should be independent of the number of legs on the connecting route. Map-learning subjects estimate orientation without reference to the connecting route. Hence route complexity should not influence the accuracy of their estimates.

<u>Prediction 22</u>. <u>The accuracy of navigation subjects' orientation judgments should be limited by the accuracy of their component leg estimates</u>. Navigation subjects compute orientation from estimated leg lengths and turning angles. Thus, the error in their orientation judgment should be at least as large as that computed from their component-leg estimates, the correct turning angles, and error-free algebraic computations using these data.

<u>EVALUATION OF PREDICTIONS</u>

We tested the predictions for the orientation task, using the data shown in Figure 3. Figure 3 contrasts the mean angular error between the true and estimated orientation of distant points for map-learning and navigation subjects. Navigation subjects estimated orientations more accurately than map-learning subjects for items with straight-line connecting routes <u>and</u> for items with more complex connecting routes. Therefore, the data in Figure 3 comprise estimates for all 42 start point-destination pairs. Figure 3 also displays the data from both the orientation task and the simulated-orientation task.

For map-learning subjects, neither orientation nor simulated orientation judgments varied across experience groups. Therefore, the data for the three map-learning groups are combined in Figure 3 and displayed as for the distance estimation data. The failure of map-learning subjects' overall accuracy to improve with overlearning confirms Prediction 17.

In contrast, as expected from Prediction 16, the navigation subjects improved with experience on both tasks ($F(2,42) = 6.86$, $p < .01$

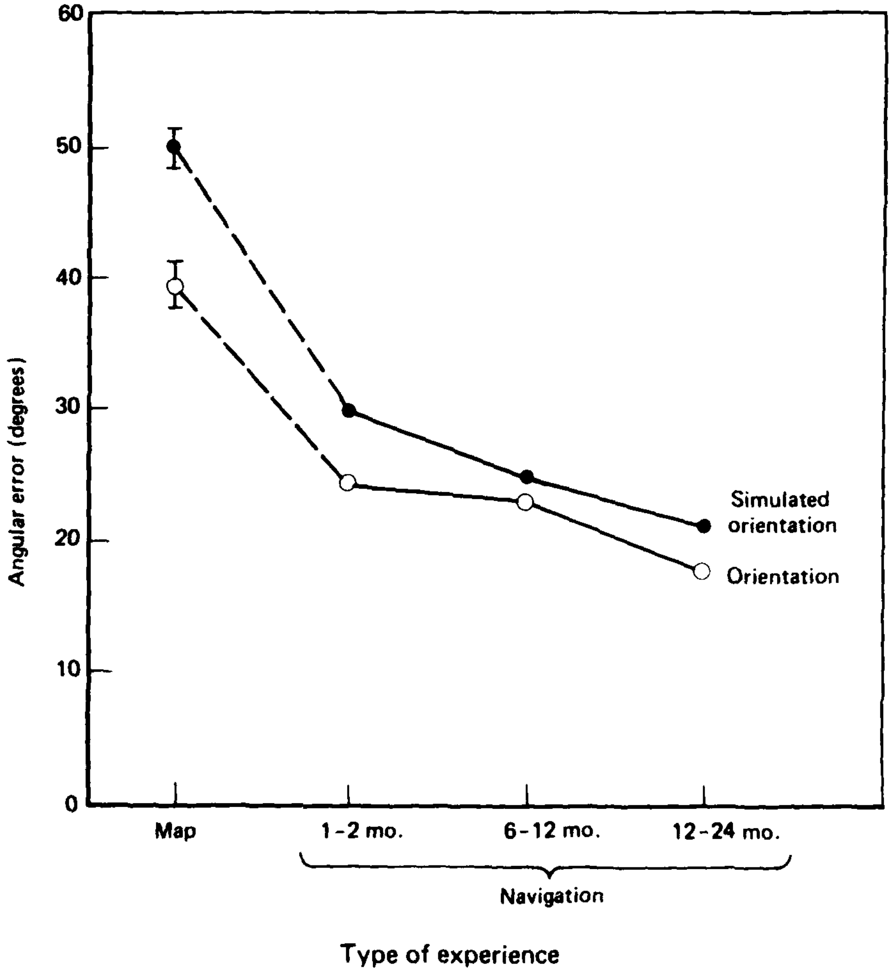

Fig. 3--Angular error on the orientation tasks

for the interaction between type and amount of learning experience). Individual comparisons showed that subjects with 1 to 2 years' experience judged orientation more accurately than subjects in the other two experience groups and they judged simulated orientation more accurately than the least experienced group ($t(42) > 1.68$, $p < .05$ for all three comparisons).

As expected from Prediction 14, navigation subjects were far more accurate than map-learning subjects ($F(1,42) = 36.13$, $p < .001$). This result held for both the orientation and simulated-orientation tasks. Performance of all subjects was more accurate on the orientation task than on the simulated-orientation task ($F(1,42) = 7.83$, $p < .01$). This difference presumably reflects the additional requirement in the simulated-orientation task of imagining oneself in the specified position at the start point. We had included the simulated-orientation task to test for an artifactual advantage that navigation subjects might have on the orientation task resulting from familiarity of local visual features. Such an artifact, if present, should have resulted in a larger between-group difference on the orientation task than on the simulated-orientation task. As Figure 3 shows, however, this result did not obtain. Since the patterns of performance and between-group differences on the two tasks were quite similar, additional analyses of orientation performance considered only the true orientation task.

Figure 4 shows the results for the location task. We scored subjects' responses both for the distance from the true location to the judged location of the destination point on the response sheet (measured in millimeters) and as the angular error in the placement of the

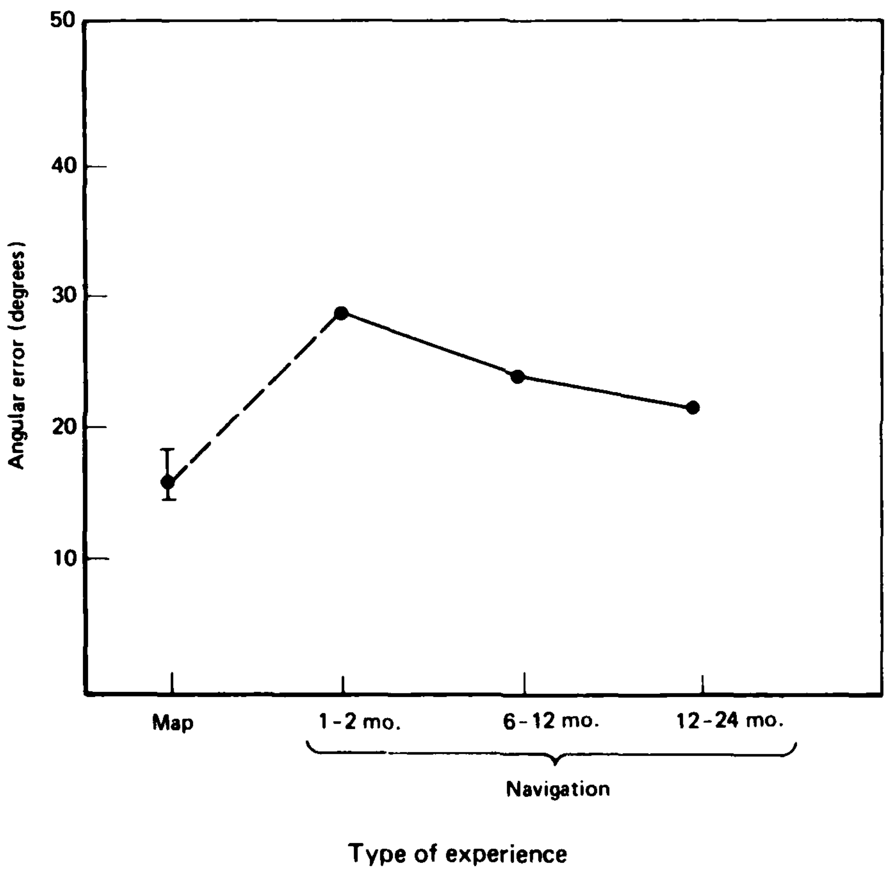

Fig. 4--Angular error on the object location task

destination point relative to the two given points. The two dependent measures produced a similar pattern of results. Therefore, to maintain consistency in the units of measurement, we have used angular error as the ordinate value in Figure 4.

As in the other tasks, the performance of map-learning subjects did not change with additional experience. However, navigation subjects did improve with experience ($\underline{F}(2,42) = 4.81$, $\underline{p} < .05$ for the interaction between type and amount of experience). Overall, map-learning subjects were more accurate than navigation subjects, as expected from Prediction 15 ($\underline{F}(1,41) = 11.10$, $\underline{p} < .01$). However, the accuracy of the most experienced navigation subjects did not differ reliably from that of the map-learning subjects ($\underline{p} > .05$).

The use of angular error as a dependent variable treats individual items independently. To obtain a more aggregated measure of subjects' cognitive maps derived from orientation and location judgments, we reconstructed their cognitive maps of the various locations using combinations of estimates for each location. For example, on the orientation task, each subject pointed toward the East Lobby from six different locations. By imposing a cartesian x-y coordinate system on the space, we characterized each of these estimates as a line passing through the start point (x_i, y_i) at an angle of a (the estimated orientation). Using the least-squares method, we determined the point in space closest to all six lines and used the coordinates of that point as the best estimate of the location of the destination point in the subject's cognitive map. We then derived two measures from this point estimate: the accuracy of the point (defined as the euclidean distance to the coordinates

of the true location) and the consistency of the estimate (defined as the standard error of the estimate obtained from the least-squares method).

Figure 5 displays the accuracy and consistency data so derived for map-learning and navigation subjects. The ordinate represents the distance in feet from the true point location from the estimated location, averaged across locations and subjects. The bars around each point indicate the mean consistency, or standard error, of each estimate. The results are consonant with the data in Figures 3 and 4. Performance among map-learning subjects did not vary with experience. For the orientation task, navigation subjects were more accurate than map-learning subjects and improved with experience. Further, the consistency in their estimates improved (i.e., the standard error decreased) with additional experience. For the location task, map-learning subjects were more accurate than navigation subjects, but navigation subjects improved with experience.

Table 8 contrasts subjects' performance on the orientation and location tasks directly. As expected from Prediction 18, navigation subjects judged orientation more accurately than object location. This prediction held for 16 of the 24 navigation subjects ($p < .05$). In contrast, 23 of the 24 map-learning subjects judged location more accurately than orientation ($p < .01$), as expected from Prediction 19.

Table 9 presents subjects' orientation performance as a function of the complexity of the connecting route between the start and destination points. Since only navigation subjects compute orientations with reference to routes, we predicted that increasing route complexity would

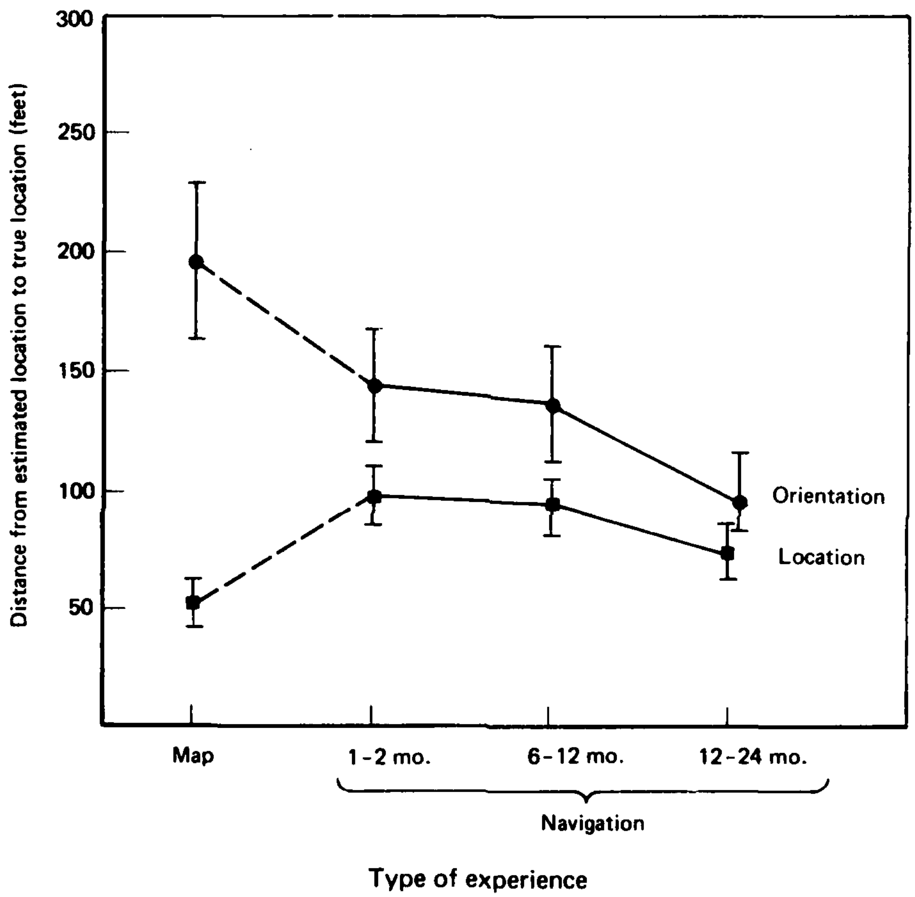

Fig. 5--Accuracy of subjects' cognitive maps as derived using least-squares method

Table 8

ANGULAR ERROR FOR ORIENTATION AND LOCATION JUDGMENTS

Type of Experience	Angular Error		Percentage of Subjects Confirming Prediction
	Orientation	Location	
Map	39.3	16.9	95.8[a]
Navigation	22.1	24.9	66.7[b]

[a] $p < .01$

[b] $p < .05$

Table 9

ANGULAR ERROR IN ORIENTATION ESTIMATES FOR LOCATION PAIRS WITH SIMPLE AND COMPLEX CONNECTING ROUTES

Type of Experience	Angular Error (Degrees)		Percentage of Subjects Confirming Prediction
	1-2 legs	4-8 legs	
Map	41.5	38.5	45.8
Navigation	17.4	30.9	91.7[a]

[a] $p < .01$

increase orientation error only for these subjects (Predictions 20 and 21). As Table 9 shows, navigation subjects were much more accurate in

their orientation judgments between points on routes with one or two component legs than on routes with from four to eight component legs. This result held for 22 of the 24 subjects. The performance of map-learning subjects, in contrast, did not vary systematically with route complexity. The result predicted for navigation subjects held for only 13 of the 24 map-learning subjects.

Finally, we tested the prediction that the accuracy of navigation subjects' orientation judgments should be limited by the accuracy of their route-leg estimates. To test this prediction, we computed for each test item the difference between the absolute value of the angular error in a subject's orientation estimate and the absolute value in the error of the estimate computed using the subject's route-leg estimates, correct values for the angles connecting the legs, and accurate algebraic computation using these data. Thus, the prediction would be confirmed for a subject whenever this mean difference was greater than or equal to zero. Across all navigation subjects, this mean difference was 20.7 degrees. On a subject-by-subject basis, this error difference was greater than or equal to zero for 21 of the 24 subjects ($p < .01$).

To summarize, map-learning subjects made more errors when judging orientation than when estimating object locations. This result derived from the additional change in perspective required of map-learning subjects when judging orientation. Neither of these judgments improved with overlearning of the map on which the judgments were based. Navigation subjects judged orientation more accurately than they judged object locations, which required perspective changes during the judgment process. With additional navigation experience, performance on both tasks

improved. Navigation subjects with minimal experience judged orientation more accurately than map-learning subjects. While map-learning subjects in general judged object locations more accurately than navigation subjects, navigation subjects with extensive experience performed as well as subjects who had learned the map. All of our nine predictions were reliably confirmed.

VI. DISCUSSION

Taken together, the data from this experiment provide a fairly consistent picture of the differences between the knowledge people acquire from maps and the knowledge they acquire from navigation. Map learners acquire a bird's-eye view of the environment that encodes survey knowledge sufficient to support performance on a variety of estimation tasks. The obvious advantage of acquiring knowledge from a map is the relative ease with which the global relationships can be perceived and learned. When using this knowledge to perform spatial judgments, individuals have direct access to the knowledge required to estimate distances and judge object locations. They are most error-prone when required to change perspective on the representation and translate their knowledge into a response within the environment, as on the orientation task. It is perhaps not intuitively clear that people who have memorized a map should have difficulty simply changing their perspective to support accurate orientation judgments. However, a common instance of this difficulty arises in another context: drawing a route map using only navigation experience. People living in environments with irregular street topography often have difficulty drawing maps of their local street network that satisfy internal, local constraints of street direction and intersection. This difficulty persists even when they have vivid and accurate memories of the routes they are attempting to reproduce. In this example, the required perspective change translates procedural knowledge into survey knowledge. Nevertheless, it illustrates the difficulty of perspective change.

Through navigation, people acquire memories of space represented in four dimensions (including time). When individuals use only this knowledge to perform spatial judgments, performance is limited by the necessity to derive judgments through computation on pieces of this knowledge (as when estimating orientation, object location, or euclidean distances). Further, performance declines when perspective changes are required to generate a response, as in the location task. The fact that subjects with navigation experience performed better on the orientation task than map-learning subjects suggests that the difficulty of changing perspective overwhelms the difficulty of computing direct judgments from circuitous route experiences. Despite the necessity to compute the orientation of a destination from knowledge only of an indirect route to the destination, navigation subjects were more accurate than map-learning subjects, who had to rotate the response plane of a directly measured angle.

The improvement in performance across experience groups on the euclidean distance estimation, orientation, and location tasks suggests that extensive navigation can lead to qualitative changes in the knowledge of the environment. One might argue that additional experience merely improved memory for the traversed routes in the environment. However, across experience, estimates of route distance remained constant while estimates of euclidean distance among the same points improved. This supports our model of the migration of people's procedural knowledge to a form of survey knowledge in which the environment is "translucent." People with extensive navigation experience can in some sense "look through" opaque obstacles in the environment to their

destination without reference to the connecting route. While we do not believe that this process is actually visual in nature, it illustrates the idea of survey knowledge from a perspective within, rather than above, the represented environment.

This model of the reorganization of procedural knowledge to survey knowledge has several implications that we have not tested. In particular, subjects who can directly access the location of a destination in such a representation should be faster at judging orientation than subjects who must simulate route traversal and compute an estimate based on this simulation. In general, reaction-time studies offer a promising paradigm in which to test several of our predictions for differential complexity in the processes required to produce spatial judgments.

Acquiring survey knowledge solely through navigation entails both costs and benefits. Our data indicate that the principal advantage of such learning is the ultimate superiority of the acquired cognitive map. On the distance-estimation tasks, highly experienced navigation subjects were superior to map-learning subjects in route estimation and equivalent in euclidean estimation. Similarly, these navigation subjects were superior to map-learning subjects on orientation judgments and equivalent on object location judgments. While, in the limit, the knowledge acquired from navigation may be more extensive than that acquired through map learning, it is obviously more difficult to obtain. Our highly experienced subjects had between one and two years of route traversals from which to derive their spatial knowledge. In contrast, the map subjects required only approximately 20 minutes to learn the map. In many situations, it may not be practical or possible to travel

in the environment repeatedly to accurate spatial knowledge.

One factor that may significantly influence the relative utility of map learning and navigation experience is the regularity of the environment. In extremely regular environments with rectangular street grids (e.g., Manhattan), navigation may rapidly lead to accurate survey knowledge. In extremely irregular environments (e.g., Boston), accurate survey knowledge develops much more slowly when based solely on navigation. The environment used in the present experiment was between these two extremes. Within each building, hallways met at right angles. However, the two buildings were separated by an obtuse angle that made between-building judgments difficult. Indeed, we observed that navigation subjects were significantly more accurate on within-building estimates of orientation and euclidean distance than on between-building estimates. In general, we would expect the differences between map-learning subjects and navigation subjects with different amounts of experience to vary as the regularity of the environment changed.

Another potential source of variation in performance that we have not addressed here is individual differences in skills and strategies for spatial-knowledge acquisition. In other studies in our laboratory, we have noted large differences in people's skill at learning from both maps and navigation (Thorndyke, 1980a; Thorndyke & Stasz, 1980). These differences are predictable from people's visual memory ability and field dependence (spatial restructuring ability). In general, subjects high in these abilities acquire an accurate representation of an environment either from a map or from navigation faster than low-ability subjects. In our study, subjects' abilities may have influenced the

amount of experience they required to develop survey knowledge from their navigation experiences.

One of the shortcomings of the spatial performance models we have proposed is that we have intimately linked our assumptions about representation and process. Our model of the knowledge people acquire led to natural assumptions about the procedures they use to compute estimates using that knowledge. The combination of assumptions about knowledge and procedures constrained our predictions for subjects' performance. However, we did not independently assess the tractability of the two sets of assumptions. It is possible that, for example, other assumptions about the procedures that subjects use to compute estimates would lead to the same predictions for performance. Strictly speaking, by obtaining data consistent with our predictions, we have only failed to reject our model rather than confirming it. However, we made our model extremely vulnerable by testing a large number of predictions (22). For all of those predictions we obtained at least weak support, and for 21 we obtained strong support. Thus, we feel that we have taken a first step toward a detailed specification of the methods people use to reason about large-scale space.

REFERENCES

Acredelo, L., H. Pick, and M. Olsen, "Environmental differentiation and familiarity as determinants of children's memory for spatial location," Developmental Psychology, Vol. 11, 1975, 495-501.

Allen, G. W., A. W. Siegel, and R. R. Rosinski, "The role of perceptual context in structuring spatial knowledge," Journal of Experimental Psychology, Vol. 4, 1978, 617-630.

Anderson, J. R., "Arguments concerning representations for mental imagery," Psychological Review, Vol. 85, 1978, 249-277.

Appleyard, D., "Why buildings are known," Environment and Behavior, Vol. 1, 1969, 131-156.

Appleyard, D., "Styles and methods of structuring a city," Environment and Behavior, Vol. 2, 1970, 100-118.

Bartram, D. J., "Comprehending spatial information: The relative efficiency of different methods of presenting information about bus routes," Journal of Applied Psychology, Vol. 65, No. 1, 1980, 103-110.

Canter, D., The Psychology of Place, St. Martin's Press, New York, 1977.

Downs, R. M., and D. Stea (eds.), Images and Environment: Cognitive Mapping and Spatial Behavior, Aldine, Chicago, 1973.

Downs, R. M., and D. Stea, Maps in Minds, Harper & Row, New York, 1977.

Evans, G. W., "Environmental cognition," Psychological Bulletin, Vol. 88, No. 2, 1980, 259-287.

Golledge, R., and G. Rushton (eds.), Spatial Choice and Spatial Behavior, Ohio State University Press, Columbus, 1976.

Golledge, R., and G. Zannaras, "Cognitive approaches to the analysis of human spatial behavior," in W. Ittleson (ed.), Environment and Cognition, Academic Press, New York, 1973.

Hardwick, D., C. McIntyre, and H. Pick, "The content and manipulation of cognitive maps in children and adults," Monographs of the Society for Research in Child Development, Vol. 41, 1976, Whole No. 166.

Hart, R. A., and G. T. Moore, "The development of spatial cognition: A review," in R. M. Downs and D. Stea (eds.), Images and Environment: Cognitive Mapping and Spatial Behavior, Aldine, Chicago, 1973.

Hayes-Roth, F., "Distinguishing theories of representation: A critique of Anderson's 'Arguments concerning mental imagery'," Psychological Review, Vol. 86, No. 4, July 1979, 376-382.

Herman, J., R. Kail, and A. Siegel, "Cognitive maps of a college campus: A new look at freshman orientation," Bulletin of the Psychonomic Society, Vol. 13, 1979, 183-186.

Herman, J. F., and A. W. Siegel, "The development of spatial representations of large-scale environments," Learning Research and Development Center, University of Pittsburgh, 1977.

Kosslyn, S. M., T. M. Ball, and B. J. Reiser, "Visual images preserve metric spatial information: Evidence from studies of image scanning," Journal of Experimental Psychology: Human Perception and Performance, Vol. 4, 1978, 47-60.

Kozlowski, L., and K. Bryant, "Sense of direction, spatial orientation, and cognitive maps," Journal of Experimental Psychology, Vol. 3, 1977, 590-598.

Kuipers, B., "Modeling spatial knowledge," Cognitive Science, Vol. 2, 1978, 129-153.

Ladd, F., "Black youths' view of their environment: Neighborhood maps," Environment and Behavior, Vol. 2, 1970, 64-79.

Lord, F. "A study of spatial orientation in children," Journal of Educational Research, Vol. 34, 1941, 481-505.

Milgram, S., and D. Jodelet, "Psychological map of Paris," in H. M. Proschansky, W. H. Ittelson, and L. G. Rivilin (eds.), Environmental Psychology (2nd ed.), Holt, Rinehart & Winston, New York, 1976.

Moore, G., and R. Golledge, Environmental Knowing, Dowden, Hutchinson, & Ross, Stroudburg, Pennsylvania, 1976.

Piaget J., and B. Inhelder, The Child's Conception of Space, Norton, New York, 1967.

Piaget, J., B. Inhelder, and A. Szeminska, The Child's Conception of Geometry, Basic Books, New York, 1960.

Shemyakin, F. N., "Orientation in space," in B. G. Ananyev et al. (eds.), Psychological Science in the USSR (Vol. 1, Pt. 1), U.S. Office of Technical Reports (#11466), 1962.

Siegel, A. W., K. C. Kirasic, and R. V. Kail, "Stalking the elusive cognitive map: The development of children's representations of geographic space," in J. F. Wohlwill and I. Altman (eds.), Human Behavior and Environment: Children and the Environment (Vol. 3), Plenum, New York, 1978.

Siegel, A. W., and S. H. White, "The development of spatial representation of large-scale environments," in H. W. Reese (ed.), Advances in Child Development and Behavior, Academic Press, New York, 1975.

Stevens, A., and P. Coupe, "Distortions in judged spatial relations," Cognitive Psychology, Vol. 10, 1978, 422-437.

Thorndyke, P., Distance Estimation from Cognitive Maps, The Rand Corporation, R-2474-ONR, November 1979.

Thorndyke, P., Performance Models for Spatial and Locational Cognition, The Rand Corporation, R-2676-ONR, December 1980(a).

Thorndyke, P., "Spatial cognition and reasoning," in J. Harvey (ed.), Cognition, Social Behavior, and the Environment, Lawrence Erlbaum Publishers, Hillsdale, New Jersey, 1980(b).

Thorndyke, P., and B. Hayes-Roth, "Spatial knowledge acquisition from maps and navigation," paper presented at Psychonomics Society Meetings, San Antonio, Texas, 1978.

Thorndyke, P., and C. Stasz, "Individual differences in procedures for knowledge acquisition from maps," Cognitive Psychology, Vol. 12, 1980, 137-175.

Wetherell, A., "Short-term memory for verbal and graphic route information," Proceedings of the Human Factors Society - 23rd Annual Meeting, The Human Factors Society, Santa Monica, 1979.

Winer, B., Statistical Principles in Experimental Design, McGraw-Hill, New York, 1962.

DEPARTMENT OF THE NAVY

1 Dr. Robert Blanchard
Navy Personnel R&D Center
Management Support Department
San Diego, CA 92151

2 Dr. Robert Breaux
Code N-711
NAVTRAEQUIPCEN
Orlando, FL 32813

3 Chief of Naval Education & Training
Liason Office
Air Force Human Resource Laboratory
Flying Training Division
William AFB, AZ 85224

4 Dr. Richard Elster
Dept. of Administrative Sciences
Naval Postgraduate School
Monterey, CA 93940

5 Dr. Pat Federico
Naval Personnel R&D Center
San Diego, CA 92152

6 Dr. John Ford
Navy Personnel R&D Center
San Diego, CA 92152

7 Dr. Henry M. Halff
Department of Psychology, C-009
University of California
La Jolla, CA 92093

8 Lt. Steven D. Harris, MCS, USN
Code 6021
Naval Air Development Center
Warminster, PA 18974

9 CDR Charles W. Hutchins
Naval Air Systems Command Hq
AIR-340F
Department of the Navy
Washington, DC 20361

10 CDR Robert S. Kennedy
Head, Human Performance Sciences
Naval Aerospace Medical Research
Laboratory
Box 29407
New Orleans, LA 70189

11 Dr. Norman J. Kerr
Chief of Naval Technical Training
Naval Air Station Memphis (75)
Millington, TN 38054

12 Dr. William L. Maloy
Principal Civilian Advisor for
Education & Training
Naval Training Command, Code 0CA
Pensacola, FL 32508

13 Dr. Kneale Marshall
Scientific Advisor to DCNO(MPT)
OP01T
Washington, D.C. 20370

14 Capt. Richard L. Martin, USN
Prospective Commanding Officer
USS Carl Vinson (CVN-70)
Newport News Shipbuilding &
Drydock Company
Newport News, VA 23607

15 Dr. George Moeller
Head, Human Factors Department
Naval Submarine Medical Research
Laboratory
Groton, CT 06340

16 Dr. William Montague
Navy Personnel R&D Center
San Diego, CA 92152

17 Naval Medical R&D Command
Code 44
National Naval Medical Center
Bethesda, MD 20014

18 Mr. William Nordbrock
Instructional Program Development
Bldg. 90
NET-PDCD
Great Lakes Naval Training Center
Illinois 60088

19 Ted M. I. Yellen
Technical Information Office,
Code 201
Naval Personnel R&D Center
San Diego, CA 92152

20 Library, Code P201L
Naval Personnel R&D Center
San Diego, CA 92152

21 Technical Director
Navy Personnel R&D Center
San Diego, CA 92152

22 Commanding Officer
Naval Research Laboratory
Code 2627
Washington, D.C. 20390

23 Psychologist
ONR Branch Office
Bldg. 114, Section D
666 Summer Street
Boston, MA 02210

24 Psychologist
ONR Branch Office
536 S. Clark Stree
Chicago, IL 60605

25 Personnel & Training Research
Programs (Code 458)
Office of Naval Research
Arlington, VA 22217

26 Psychologist
ONR Branch Office
1030 East Green Street
Pasadena, CA 91101

27 Office of the Chief of Naval
Operations
Research Development & Studies
Branch (OP-115)
Washington, D.C. 20350

28 Lt. Frank C. Petho, MSC, USN (Ph.D.)
Code L51
Naval Aerospace Medical Research
Laboratory
Pensacola, FL 32508

29 Dr. Gary Poock
Operations Research Department
Code 55PK
Naval Postgraduate School
Monterey, CA 93940

30 Roger W. Remington, Ph.D.
Code L52
NAMRL
Pensacola, FL 32508

31 Mr. Arnold Rubenstein
Naval Personnel Support Technology
Naval Material Command (08T244)
Room 1044, Crystal Plaza #5
2221 Jefferson Davis Highway
Arlington, VA 20360

32 Dr. Worth Scanland
Chief of Naval Education & Training
Code N-5
NAS
Pensacola, FL 32508

33 Dr. Robert G. Smith
Office of Chief of Naval Operations
OP-987H
Washington, DC 20350

34 Dr. Alfred F. Smode
Training Analysis & Evaluation
Group (TAEG)
Department of the Navy
Orlando, FL 32813

35 Dr. Richard Sorensen
Navy Personnel R&D Center
San Diego, CA 92152

36 Dr. Robert Wisher
Code 309
Naval Personnel R&D Center
San Diego, CA 92152

DEPARTMENT OF THE ARMY

37 HQ USAREUE & 7th Army
ODCSOPS
USAAREUE Director of GED
APO New York 09403

38 Dr. Ralph Dusek
U.S. Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

39 Dr. Frank J. Harris
U.S. Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

40 Col. Frank Hart
Army Research Institute for the
Behavioral & Social Sciences
5001 Eisenhower Blvd.
Alexandria, VA 22333

41 Dr. Michael Kaplan
U.S. Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

42 Dr. Milton S. Katz
Training Technical Area
U.S. Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

43 Director
U.S. Army Human Engineering Labs
Attn: DRXHE-DB
Aberdeen Proving Ground, MD 21005

44 Dr. Harold F. O'Neil, Jr.
Attn: PERI-OK
Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

45 Dr. Robert Sasmor
U.S. Army Research Institute for
the Behavioral & Social Sciences
5001 Eisenhower Avenue
Alexandria, VA 22333

46 Dr. Joseph Ward
U.S. Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

DEPARTMENT OF THE AIR FORCE

47 Air University Library
AUL/LSE 76/443
Maxwell AFB, AL 36112

48 Dr. Earl A. Alluisi
Hq AFHRL (AFSC)
Brooks AFB, TX 78235

49 Dr. Genevieve Haddad
Program Manager
Life Sciences Directorate
AFOSR
Bolling Air Force Base
Washington, D.C. 20332

50 Dr. Ross L. Morgan
(AFHRL/LR)
Wright-Patterson AFB, OH 45433

51 Dr. Marty Rockway
(AFHRL/TT)
Lowry AFB, CO 80230

52 3700 TCHTW/TTGH
Stop 32
Sheppard AFB, TX 76311

53 Major Jack A. Thorpe, USAF
Naval War College
Providence, RI 02846

DEPARTMENT OF THE MARINES

54 H. William Greenup
Education Advisor (E031)
Education Cetner, MCDEC
Quantico, VA 22134

55 Major Howard Langdon
Hq., Marine Corps
OTTI 31
Arlington Annex
Columbia Pike at Arlington Ridge Rd.
Arlington, VA 20380

56 Special Assistant for Marine
Corps Matters
Code 100M
Office of Naval Research
800 N. Quincy Street
Arlington, VA 22217

57 Dr. A. L. Slafkosky
Scientific Advisor (Code RD-1)
Hq., U.S. Marine Corps
Washington, D.C. 20380

DEPARTMENT OF DEFENSE

58 Dr. Craig I. Fields
Advanced Research Projects Agency
1400 Wilson Blvd.
Arlington, VA 22209

59 Dr. Dexter Fletcher
Advanced Research Projects Agency
1400 Wilson Blvd.
Arlington, VA 22209

60 Cdr. Van K. Nield, USN
Code STT
Hq., Defense Mapping Agency
Building 56
Naval Observatory
Washington, D.C. 20305

61 Military Asst. for Training &
Personnel Technology
Office of the Under Secretary of
Defense for Research & Engineering
Washington, D.C. 20301

OTHER GOVERNMENT AGENCIES

62 Dr. Susan Chipman
Learning & Development
National Institute of Education
1200 - 19th Street, N.W.
Washington, D.C. 20208

63 Dr. Joseph I. Lipson
SEDR W-638
National Science Foundation
Washington, D.C. 20550

64 Dr. John Mays
National Institute of Education
1200 - 19th Street, N.W.
Washington, D.C. 20208

65 Dr. Arthur Melmed
National Institute of Education
1200 - 19th Street, N.W.
Washington, D.C. 20208

66 Dr. Andrew R. Molnar
Science Education Development & Research
National Science Foundation
Washington, D.C. 20550

67 Dr. Joseph L. Young, Director
Memory & Cognitive Processes
National Science Foundation
Washington, D.C. 20550

ADDITIONAL ADDRESSES

68 Dr. John R. Anderson
Department of Psychology
Carnegie Mellon University
Pittsburgh, PA 15213

69 Dr. Michael Atwood
Science Applications Institute
40 Denver Tech. Center West
7935 E. Prentice Avenue
Englewood, CO 80110

70 1 Psychological Research Unit
Dept. of Defense (Army Office)
Campbell Park Offices
Canberra ACT 2600, Australia

71 Dr. Alan Baddeley
Medical Research Council
Applied Psychology Unit
15 Chaucer Road
Cambridge CB2 2EF
ENGLAND

72 Dr. Patricia Baggett
Department of Psychology
University of Denver
University Park
Denver, CO 80208

73 Dr. Nicholas A. Bond
Dept. of Psychology
Sacramento State College
600 Jay Street
Sacramento, CA 95819 Non Govt

74 Dr. Lyle Bourne
Department of Psychology
University of Colorado
Boulder, CO 80309

75 Dr. John S. Brown
XEROX Palo Alto Research Center
3333 Coyote Road
Palo Alto, CA 94304

76 Dr. Bruce Buchanan
Department of Computer Science
Stanford University
Stanford, CA 94305

77 Dr. Pat Carpenter
Department of Psychology
Carnegie-Mellon University
Pittsburgh, PA 15213

78 Dr. John B. Carroll
Psychometric Lab
Univ. of No. Carolina
Davie Hall 013A
Chapel Hill, NC 27514

79 Charles Myers Library
Livingstone House
Livingstone Road
Stratford
London E15 2LJ
ENGLAND

80 Dr. William Chase
Department of Psychology
Carnegie Mellon University
Pittsburgh, PA 15213

81 Dr. Micheline Chi
Learning R & D Center
University of Pittsburgh
3939 O'Hara Street
Pittsburgh, PA 15213

82 Dr. Kenneth E. Clark
College of Arts & Sciences
University of Rochester
River Campus Station
Rochester, NY 14637

83 Dr. Allan M. Collins
Bolt Beranek & Newman, Inc.
50 Moulton Street
Cambridge, Ma 02138

84 Dr. Lynn A. Cooper
Department of psychology
Uris Hall
Cornell University
Ithaca, NY 14850

85 Dr. Meredith P. Crawford
American Psychological Association
1200 17th Street, N.W.
Washington, DC 20036

86 Dr. Kenneth B. Cross
Anacapa Sciences, Inc.
P.O. Drawer Q
Santa Barbara, CA 93102

87 Dr. Hubert Dreyfus
Department of Philosophy
University of California
Berkeley, CA 94720

88 LCOL J. C. Eggenberger
Directorate Of Personnel Applied
Research
National Defence HQ
101 Colonel By Drive
Ottawa,
CANADA K1A OK2

89 Dr. Victor Fields
Department of Psychology
Montgomery College
Rockville, MD 20850

90 Dr. Edwin A. Fleishman
Advanced Research Resources Organ.
Suite 900
4330 East West Highway
Washington, DC 20014

91 Dr. John D. Folley, Jr.
Applied Sciences Associates, Inc.
Valencia, PA 16059

92 Dr. John R. Frederiksen
Bolt Beranek & Newman
50 Moulton Street
Cambridge, MA 02138

93 Dr. Alinda Friedman
Department of Psychology
University of Alberta
Edmonton, Alberta
CANADA T6G 2E9

94 Dr. R. Edward Geiselman
Department of Psychology
University of California
Los Angeles, CA 90024

95 DR. ROBERT GLASER
LRDC
UNIVERSITY OF PITTSBURGH
3939 O'HARA STREET
PITTSBURGH, PA 15213

96 Dr. Marvin D. Glock
217 Stone Hall
Cornell University
Ithaca, NY 14853

97 DR. JAMES G. GREENO
LRDC
UNIVERSITY OF PITTSBURGH
3939 O'HARA STREET
PITTSBURGH, PA 15213

98 Dr. Harold Hawkins
Department of Psychology
University of Oregon
Eugene, OR 97403

99 Mr. Richards J. Heuer, Jr.
27585 Via Sereno
Carmel, CA 92923

100 Dr. James R. Hoffman
Department of Psychology
University of Delaware
Newark, DE 19711

101 Dr. Lloyd Humphreys
Department of Psychology
University of Illinois
Champaign, IL 61820

102 Dr. Earl Hunt
Dept. of Psychology
University of Washington
Seattle, WA 98105

103 Dr. Kay Inaba
21116 Vanowen Street
Canoga Park, CA 91303

104 DR. LAWRENCE B. JOHNSON
LAWRENCE JOHNSON & ASSOC., INC.
Suite 103
4545 42nd Street, N.W.
Washington, DC 20016

105 Dr. Steven W. Keele
Dept. of Psychology
University of Oregon
Eugene, OR 97403

106 Dr. Walter Kintsch
Department of Psychology
University of Colorado
Boulder, CO 80302

107 Dr. David Kieras
Department of Psychology
University of Arizona
Tuscon, AZ 85721

108 Dr. Kenneth A. Klivington
Program Officer
Alfred P. Sloan Foundation
630 Fifth Avenue
New York, NY 10111

109 Dr. Stephen Kosslyn
Harvard University
Department of Psychology
33 Kirkland Street
Cambridge, MA 02138

110 Mr. Marlin Kroger
1117 Via Goleta
Palos Verdes Estates, CA 90274

111 Dr. Jill Larkin
Department of Psychology
Carnegie Mellon University
Pittsburgh, PA 15213

112 Dr. Alan Lesgold
Learning R&D Center
University of Pittsburgh
Pittsburgh, PA 15260

113 Dr. Robert A. Levit
Director, Behavioral Sciences
The BDM Corporation
7915 Jones Branch Drive
McClean, VA 22101

114 Dr. Charles Lewis
Faculteit Sociale Wetenschappen
Rijksuniversiteit Groningen
Oude Boteringestraat
Groningen
NETHERLANDS

115 Dr. Allen Munro
Behavioral Technology Laboratories
1845 Elena Ave., Fourth Floor
Redondo Beach, CA 90277

116 Dr. Donald A Norman
Dept. of Psychology C-009
Univ. of California, San Diego
La Jolla, CA 92093

117 Dr. Jesse Orlansky
Institute for Defense Analyses
400 Army Navy Drive
Arlington, VA 22202

118 MR. LUIGI PETRULLO
2431 N. EDGEWOOD STREET
ARLINGTON, VA 22207

119 Dr. Martha Polson
Department of Psychology
University of Colorado
Boulder, CO 80302

120 DR. PETER POLSON
DEPT. OF PSYCHOLOGY
UNIVERSITY OF COLORADO
BOULDER, CO 80309

121 DR. DIANE M. RAMSEY-KLEE
R-K RESEARCH & SYSTEM DESIGN
3947 RIDGEMONT DRIVE
MALIBU, CA 90265

122 Dr. Fred Reif
SESAME
c/o Physics Department
University of California
Berkely, CA 94720

123 Dr. Andrew M. Rose
American Institutes for Research
1055 Thomas Jefferson St. NW
Washington, DC 20007

124 Dr. Ernst Z. Rothkopf
Bell Laboratories
600 Mountain Avenue
Murray Hill, NJ 07974

125 Dr. David Rumelhart
Center for Human Information
Processing
University of California
La Jolla, CA 92093

126 DR. WALTER SCHNEIDER
DEPT. OF PSYCHOLOGY
UNIVERSITY OF ILLINOIS
CHAMPAIGN, IL 61820

127 Dr. Alan Schoenfeld
Department of Mathematics
Hamilton College
Clinton, NY 13323

128 Dr. Robert J. Seidel
Instructional Technology Group
HUMRRO
330 N. Washington Street
Alexandria, VA 22314

129 Dr. Robert Smith
Department of Computer Science
Rutgers University
New Brunswick, NJ 08903

130 Dr. Richard Snow
School of Education
Stanford University
Stanford, CA 94305

131 Dr. Robert Sternberg
Dept. of Psychology
Yale University
Box 11A, Yale Station
New Haven, CT 06520

132 DR. ALBERT STEVENS
BOLT BERANEK & NEWMAN, INC.
50 MOULTON STREET
CAMBRIDGE, MA 02138

133 Dr. David Stone
ED 236
SUNY, Albany
Albany, NY 12222

134 DR. PATRICK SUPPES
INSTITUTE FOR MATHEMATICAL
STUDIES IN THE SOCIAL SCIENCES
STANFORD UNIVERSITY
STANFORD, CA 94305

135 Dr. Douglas Towne
Univ. of So. California
Behavioral Technology Labs
1845 S. Elena Ave.
Redondo Beach, CA 90277

136 Dr. J. Uhlaner
Perceptronics, Inc.
6271 Variel Avenue
Woodland Hills, CA 91364

137 Dr. Benton J. Underwood
Dept. of Psychology
Northwestern University
Evanston, IL 60201

138 Dr. David J. Weiss
N660 Elliott Hall
University of Minnesota
75 E. River Road
Minneapolis, MN 55455

139 Dr. Christopher Wickens
Department of Psychology
University of Illinois
Champaign, IL 61820

140 Dr. J. Arthur Woodward
Department of Psychology
University of California
Los Angeles, CA 90024

141 Library of Congress
Program Manager, CIP Program
Descriptive Cataloging Division
Washington, DC 20540

141 ADDRESSES
141 TOTAL COPIES

ND

ATE